A hyperelastic model for cardiac deformation applied to multimodal registration of MRI and optical mapping data

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Keywords : nonlinear hyperelasticity ; cardiac mechanical modelling ; multimodal registration ; finite elements ; Newton's method ; Holzapfel–Ogden model.

Motivation. Understanding the relationship between cardiac structure and function requires combining different imaging modalities. In this context, magnetic resonance imaging (MRI) and optical mapping provide complementary information on the same cardiac tissue, but in two markedly different configurations. MRI gives access to the geometry and microstructural organization of the myocardium in its resting state, whereas optical mapping is performed on a stretched and flattened tissue sample and provides functional information. Establishing a **geometric mapping** between these two modalities therefore requires a model for the mechanical deformation undergone by the tissue.

Main idea. We describe this geometric transfer by a nonlinear elasticity problem posed on a reference domain Ω_0, representing the resting configuration of the heart. More precisely, we seek a deformation

$$\varphi(x) = x + \mathbf{u}(x),$$

mapping Ω_0 onto the stretched configuration observed in the optical mapping experiment. The associated displacement field $\mathbf{u}$ is obtained as a minimizer of the following total energy

$$\mathcal{E}(\mathbf{u}) = \underbrace{\int_{\Omega_0} W(\mathbf{u})\,dx}_{\text{internal elastic energy}} \underbrace{-\int_{\Omega_0} \mathbf{f}\cdot\mathbf{u}\,dx - \int_{\Gamma_N} \mathbf{g}\cdot\mathbf{u}\,ds}_{\text{external work}},$$

where $\mathbf{f}$ denotes a body force, $\mathbf{g}$ a boundary traction, and $\Gamma_N \subset \partial\Omega_0$ the part of the boundary on which traction is prescribed.

The stored energy density W is chosen of Holzapfel–Ogden type and is decomposed as

$$W = \underbrace{W_{\text{iso}}}_{\text{isochoric part}} + \underbrace{W_{\text{vol}}}_{\text{volumetric contribution}}$$

where the isochoric contribution accounts for non linearity and for transverse isotropy induced by the myocardial fiber architecture, while the volumetric term enforces near-incompressibility.

We present a first test case based on a conforming Lagrange finite element discretization on a two-dimensional annular geometry. The resulting nonlinear system is solved by Newton's method combined with a line-search procedure. This result suggests that the proposed framework is able to capture substantial deformations in a consistent way, which is encouraging for future applications to real experimental data.

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